APPLICATION

FOR

UNITED STATES LETTERS PATENT

SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

Be it known that, Charles Tapalian, citizen of the United States of America, and residing in 359-1F Bolivar Street, Canton, MA 02021, and Juha-Pekka Laine, citizen of Finland, and residing in 534 Beacon Street, Apt. 801, Boston, MA 02215, have invented certain improvements in a **Micro-optic Absorption Spectrometer** in which the following description in connection with the accompanying drawings is a specification, like reference characters on the drawings indicating like parts in the several figures.

MICRO-OPTIC ABSORPTION SPECTROMETER

CROSS-REFERENCE TO RELATED APPLICATIONS

Not Applicable

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

Not Applicable

REFERENCE TO MICROFICHE APPENDIX

Not Applicable

FIELD OF THE INVENTION

The present invention relates to optical sensors, and in particular to a high-precision, micro-optic absorption spectrometer.

BACKGROUND OF THE INVENTION

During the past few years, a substantial amount of research has been performed in the field of optical microcavity physics, in order to develop high cavity-Q optical microcavity resonators. In general, resonant cavities that can store and recirculate electromagnetic energy at optical frequencies have many useful applications, including high-precision spectroscopy, signal processing, sensing, and filtering. Many difficulties present themselves when conventional planar technology, i.e. etching, is used in order to fabricate high quality optical resonators, because the surfaces must show deviations of less than about a few nanometers. Optical microsphere resonators, on the other hand, can have quality factors that are several orders of magnitude better than typical surface etched optical micro-resonators, because these microcavities can be shaped by natural surface

tension forces during a liquid state fabrication. These microcavities are inexpensive, simple to fabricate, and are compatible with integrated optics.

Optical microcavity resonators have quality factors (Qs) that are higher by several orders of magnitude, as compared to other electromagnetic devices. Measured Qs as large at 10^{10} have been reported. The high-Q resonances encountered in these microcavities are due to whispering-gallery-modes (WGM) that are supported within the microcavities.

As a result of their small size and high cavity Q, interest has recently grown in potential applications of microcavities to fields such as electro-optics, microlaser development, measurement science, and spectroscopy. By making use of these high Q values, microspheric cavities have the potential to provide unprecedented performance in numerous applications. For example, these microspheric cavities may be useful in applications that call for ultra-narrow linewidths, long energy decay times, large energy densities, and fine sensing of environmental changes, to cite just a few examples.

In order for the potential of microcavity-based devices to be realized, it is necessary to couple light selectively and efficiently into the microspheres. Since the ultra-high Q values of microcavities are the result of energy that is tightly bound inside the cavity, optical energy must be coupled in and out of the high Q cavities, without negatively affecting the Q. Further, the stable integration of the microcavities with the input and output light coupling media should be achieved. Also, controlling the excitation of resonant modes within these microcavities is necessary for proper device performance, but presents a challenge for conventional waveguides.

Typically, good overall performance is gained by accessing the evanescent field in a waveguide. Also, only waveguide structures provide easy alignment and discrete, clearly defined ports. Because of cavity and waveguide mode leakage into the substrate and into the modes within the fiber cladding, power extraction from the input optical radiation has proved to be inefficient for conventional planar waveguides, however.

U.S. Patent Application Serial No. ___ (identified by Attorney Docket Nos. CSLL-625 and hereby incorporated by reference)(hereinafter the "CSLL-625" application) discloses a highly efficient and robust mechanism for coupling optical microcavity whispering-gallery modes into integrated optical waveguide chips. SPARROW (Stripline Pedestal Antiresonant Reflecting Waveguides) are used to achieve vertical confinement and substrate isolation through a highly reflective stack of alternating high and low refractive index dielectric layers. Q-values of over 10^{10}, and coupling efficiencies of over 98% have been observed.

SPARROW waveguide chips have the potential to integrate optical microcavities into miniaturized optical sensor systems. Because of their ability to excite resonant modes having unprecedentedly high Q-values in optical microcavities, SPARROW waveguide chips have the potential for greatly increasing the resolution and dynamic range in these sensing applications.

In particular, a significant potential application for microcavity resonator devices is chemical / biological agent sensing. Chemical sensors known in the art include MEMS (microelectromechanical systems) chemical sensors, optical waveguide-based sensors, surface plasmon resonance (SPR) chemical sensors, surface acoustic wave (SAW) chemical sensors, mass spectrometers, and IR (infrared) absorption spectrometers.

Miniaturized sensors, such as prior art MEMS sensors, provide significant advantages. For example, they would be well adapted for *in situ* functioning. Also, they would be small enough to be deployed in large numbers and implemented for remote probing.

It is desirable to provide chemical sensors with an improved resolution, while maintaining the compact size of MEMS sensors known in the art.

SUMMARY OF THE INVENTION

The present invention is directed to a light absorption spectrometer, formed of a waveguide-coupled optical microcavity resonator. The present invention features the tuning of the optical resonance frequency of the microsphere, to coincide with a selected electronic or vibrational transition frequency, so that the light coupled into the microsphere will experience absorption in the presence of an atomic or molecular substance surrounding the microsphere.

An infrared absorption spectrometer constructed in accordance with the present invention includes at least one optical microcavity, and an optical waveguide for coupling light into a resonant mode of the optical microcavity. The optical waveguide has an input end and an output end. The waveguide is adapted for transmitting optical radiation incident on the input end to the output end.

The light coupled into the optical microcavity is adapted to interact with at least one an atomic or molecular species. The atomic or molecular species may be found in a chemical substance surrounding the microcavity, and may be a fluid, by way of example. The optical microcavity is configured so that the frequency of at least one resonant mode of the optical cavity matches an electronic or vibrational transition frequency of the atomic or molecular species. In this way, optical radiation coupled into the optical microcavity and having a frequency substantially equal to the frequency of the resonant mode is absorbed by the atomic or molecular species.

Because of the high Q value and the correspondingly long optical path length of the optical microcavity, the sensitivity of the infrared absorption spectrometer of the present invention is significantly increased, as compared to the prior art.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of an infrared absorption spectrometer, constructed in accordance with the present invention.

Figure 2 illustrates a SPARROW optical waveguide, constructed in accordance with the present invention.

Figure 3 illustrates an optical waveguide constructed in accordance with the present invention, and having a Mach-Zehnder interferometric configuration.

DETAILED DESCRIPTION

The present invention is directed to an infrared (IR) absorption spectrometer, formed of a waveguide-coupled optical microcavity resonator. Optical microcavities are characterized by high Q values and correspondingly long optical path lengths, allowing a significant increase in the sensitivity of the infrared absorption spectrometer, as compared to prior art absorption spectrometers.

Figure 1 is a schematic diagram of an infrared absorption spectrometer 10, constructed in accordance with the present invention. The spectrometer 10 includes at least one optical microcavity resonator 12, and a waveguide 18 for evanescently coupling light from the waveguide 18 onto the microcavity 12. In the present invention, the optical resonance frequency of the microcavity is tuned to coincide with a vibrational resonance frequency of the interacting molecule, such that the light coupled into the microsphere will experience absorption in the presence of the chemical vapor surrounding the microsphere. An optical source 15, preferably a laser, provides a beam 16 of input radiation directed to the waveguide. A photodetector 17 detects optical radiation transmitted through the waveguide 18.

The optical microcavity 12 is a small spherical particle, disk, or ring, having dimensions of the order of microns to millimeters. The optical microcavity 12 is typically made of silica. In a preferred embodiment, the optical microcavity 12 is fabricated by surface tension shaping of the tip of freshly melted optical fiber. Melting of the tip of a silica wire or fiber may be accomplished through arcing in a fusion splicer, by means of a gas flame, or using a high-power laser (such as a CO_2 laser) to heat the glass. Microcavities, with diameters typically ranging from about 50 micrometers to about 500

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micrometers, are obtained by this method. In the illustrated embodiment, the optical

microcavity has a diameter of about 200 micrometers, although other sizes are also within

the scope of the present invention.

The optical microcavity 12 is adapted to support WGMs (whispering-gallery-

modes), and is thus characterized by extremly high Q values. Light incident on an input

end of the waveguide and propagating therethrough is evanescently coupled onto WGM

resonances supported within the optical microcavity. An evanescent wave appears

whenever a light wave undergoes total internal reflection at a dielectric interface, such as

the interface between the silica waveguide and the surrounding air. The evanescent

portion of the waveguide mode field is the exponentially decaying portion of the

waveguide mode field, outside the relatively high index region of the waveguide. The

evanescent wave decays exponentially with the distance from the surface of the

waveguide core on a length scale of the order of the optical wavelength.

Evanescent coupling occurs between the waveguide and the microcavity when the

wavelength of the evanescent field of the waveguide mode field matches the wavelength

of a resonant WGM supported within the microcavity. In a resonant WGM, light is

trapped near the surface of the microcavity by repeated total internal reflections, and

travels in a circle around the microcavity near the surface of the microcavity. When

WGM resonances are excited in the microcavity, light continues to circulate just inside

the surface of the microcavity, with virtually no loss except for residual absorption and

scattering in the dielectric. This is why extremely high Q-factors, up to over 10^{10}, can be

achieved in the dielectric microcavities constructed in accordance with the present

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invention. These very high Qs translate into very high optical path lengths, and hence increased sensitivity of the spectrometer.

In a preferred embodiment, the optical waveguide is a SPARROW (stripline pedestal anti-resonant reflective optical waveguide) waveguide. Figure 2 illustrates a SPARROW optical waveguide, constructed in accordance with the present invention. The SPARROW waveguide 110 provides an efficient and robust coupling mechanism for exciting whispering-gallery-modes in an optical microcavity 102. The SPARROW 110 includes a multi-layer, high-reflectivity dielectric stack 130 disposed on the substrate 120, and a waveguide core 140. The substrate 120 is substantially planar, and in one embodiment is made of silicon.

The dielectric stack 130 is composed of alternating high (n_H) and low (n_L) refractive index layers 131 and 132, made of a dielectric material. As a result, the dielectric stack 130 functions as a high reflectivity dielectric mirror. The larger the number of layers 131 and 132, the higher the reflectivity of the stack 130 becomes. While the illustrated embodiment includes only one low index layer 132 disposed between two high index layers 131, the number of the layers 131 and 132 can be increased in order to increase the reflectivity of the stack 130. The alternating layers 131 and 132 forming the dielectric stack 130 provide a cladding for the SPARROW waveguide core 140, i.e. the layers forming the stack 130 may be regarded as cladding layers.

The high reflectivity of the dielectric stack 130 permits isolation of the optical modes of the microcavity 102 and the waveguide core 140 from the waveguide cladding and the substrate. By isolating the waveguide core 140 using the high-reflectivity

dielectric stack 130, the SPARROW 110 circumvents the need for obtaining low

refractive index cladding materials. As shown in Figure 2, one of the high refractive

index layers 131 is in contact with the substrate 120.

In one embodiment, the high refractive index layer 131 is made of Si (silicon),

while the low refractive index layer 132 is made of SiO_2 (silica). In one embodiment, the

high refractive index n_H is about 3.5, and the low refractive index n_L is about 1.45,

although other refractive indices are also within the scope of the present invention. The

refractive indices required for efficiently guiding light within the waveguide depend on

the wavelength of optical radiation.

The waveguide core 140 is disposed on top of the dielectric stack 130, and is in

contact with another one of the high refractive index layers 131. The waveguide core 140

includes an input end 142 and an output end 144, and is adapted for transmitting optical

radiation incident on the input end 142 to the output end 144. In one embodiment, the

waveguide core is made of silica, and is characterized by the low refractive index n_L. In a

SPARROW waveguide, the waveguide mode field is essentially entirely contained within

the waveguide core 140 on top of the dielectric stack 130, and is isolated from the

substrate 120. The successful elimination of both the microcavity mode and the

waveguide mode leakage into the substrate results in extremely high coupling

efficiencies. Coupling efficiencies approaching 100% have been observed.

Figure 3 illustrates an optical waveguide constructed in accordance with the

present invention, and having a Mach-Zehnder like interferometric configuration. In a

Mach-Zehnder interferometer, an incoming optical signal is split into two signals, for

example at a Y-junction. Each signal enters a first and a second waveguide branch,

respectively. The signals are recombined into an output waveguide, which provides a modulated optical output signal. An electric field applied to one or both of the waveguide branches causes a change in the refractive index in the applied region, corresponding to the changing amplitude of the modulating signal. The change in the index of refraction alters the speed of light in the region, resulting in a change in the delay time of the light passing through the region. The optical path length in one or both of the waveguides branches can be controlled, so that a phase difference results between the two signals when they are recombined at the output waveguide.

The waveguide 500 has an input end 510 and an output end 512. The interferometric waveguide 500 includes three waveguide arms 505, 506, and 507. The first arm 505 forms an input channel, and is adapted to input coupling light into the microsphere. The second arm 506 forms a drop channel, and is adapted to out-couple light from the microcavity into the waveguide. The third arm 507 is used as a reference channel, which has substantially no interaction with the microcavity. At the output end 512, light from the reference channel 507 is combined or interfered with light from the drop channel, i.e. light that has interacted with the microsphere.

The sensitivity of absorption-based sensors is proportional to the optical path length. The change in phase experienced by the resonant light and measured by the interferometer may be expressed in terms of the cavity lifetime $\tau(d)$ of the microcavity, and the optical path difference (OPD) $l(d)$. The cavity lifetime $\tau(d)$ for resonant light can be expressed as a function of the total cavity Q:

$$\tau(d) = \frac{Q(d)}{\omega}$$

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Assuming interferometer arms of equal path length, the optical path length $l(d)$ can be expressed as a function of the cavity lifetime,

$$l(d) = \frac{c}{n}\tau(d) = \frac{\lambda}{2\pi\, n}Q(d)$$

From the equation provided above, it can be seen that high-Q microcavities provide a way to obtain the high sensitivities associated with long path lengths in a miniature sensor package. In contrast, the optical path lengths available on integrated optical chips are limited, resulting in reduced sensitivity. Using fused silica microcavities as described above, optical path lengths as long as 100 m can be achieved.

In the present invention, the optical resonance frequency of the microsphere is "tuned" to coincide with a selected electronic or vibrational transition frequency such that the light coupled into the microsphere will experience absorption in the presence of an atomic or molecular substance surrounding the microsphere. The result is a change in the measured light transmittance.

The technique of the present invention, when applied to IR absorption spectroscopy, takes advantage of the large absorption coefficients of molecular vibrations in the mid-IR region of the electromagnetic spectrum, typically ranging from about 3 μm to about 20 μm. Small molecules, typically 4 atoms or less, possess strong vibrational transitions toward the lower end of the infrared spectrum. The fraction of light absorbed by a molecular sample is given by

$$I_\alpha\, /\, I_0 = 1 - e^{-\alpha p L},$$

where I_a is the absorbed laser intensity;

       I_0 is the incident laser intensity;

       α is the absorption coefficient;

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p is the vapor pressure of the molecular vapor;

and L is the absorption length, i.e. optical path length.

In one embodiment, the resonant wavelength of fused silica microcavities can be shifted into the mid-infrared region, by coating the microcavities with a gold nanoshell, i.e. a layer of gold having a thickness of the order of nanometers.

In an exemplary embodiment, the infrared absorption technique described above may be implemented using methane, which has a 3.3 μm vibrational transition. Using an optical microcavity having an optical path length of 50 cm, and an absorption measurement resolution of 10^{-6}, the methane detection sensitivity is approximately 100 ppt (parts per trillion).

Because of the high-Q values and ensuing large optical path lengths of microcavity resonators, the infrared absorption spectrometer disclosed in the present invention provides a significantly increased sensitivity, as compared to prior art miniature infrared absorption spectrometer. The infrared absorption spectrometer, constructed in accordance with the present invention, provides all the advantages of a compact size, in combination with its high sensitivity. The present invention may have wide ranging applications in the industry and the military, including but not limited to the fields of manufacturing process control, environmental monitoring, combustion bi-product monitoring, and chemical/biological agent sensing on the battlefield.

While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.